Arbitrary Inductance Calculator User's Manual

By Robert J Distinti M.S. ECE
46 Rutland Ave.
Fairfield Ct 06825.

This document details the use of the Arbitrary Inductance (ArbI) calculating software.

This software uses New Electromagnetism to calculate the inductance of inductors. This software is a limited version of the software developed for my master thesis; see www.distinti.com/docs/neThesis.pdf.

This software is limited as follows:

1) Copper structures with dimensions no less than 100 microns (0.1 mils).
2) Core materials with $\mu_R = 1, \varepsilon_R = 1$ (same as free space)
3) Low frequency
    a. Skin depth larger than max cross section of inductor under test
    b. Low frequency inductors (wavelength of highest frequency componenet at least 4 time longer than length of inductor under test: wavelength=c/freq);

Please Read

This software is distributed freely and is intended solely for experimental purposes. This software is not intended to be used for any other purpose what so ever. www.distinti.com assumes no liability for the use of this software or the use of the results produced by this software for any purpose.

ArbInd Manual

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1 Installation

1.1 System requirements:

1) Microsoft Windows (Me, 2000, Xp, NT) – it should run under Vista.
2) 250Mb Minimum memory (estimated)
3) OpenGL compatible graphics card (most cards are compatible).

1.2 Installation

The installation of this software is very simple. Follow the steps below:

1) Create a new directory on your hard drive (Example c:\arbInd\)
2) Copy the files listed below from the website to your new directory
3) Installation is complete. See next section to run the code.

These are the files:

1) ArbInd.exe (the application)
2) borlndmm.dll
3) cc3270mt.dll
4) dbrtl100.bpl
5) rtl100.bpl
6) vcl100.bpl
7) vclactnband100.bpl
8) vcldb100.bpl
9) vclx100.dll

This software does not affect your Windows installation in any way.

To uninstall the software: simply delete the directory containing the above files from your computer.

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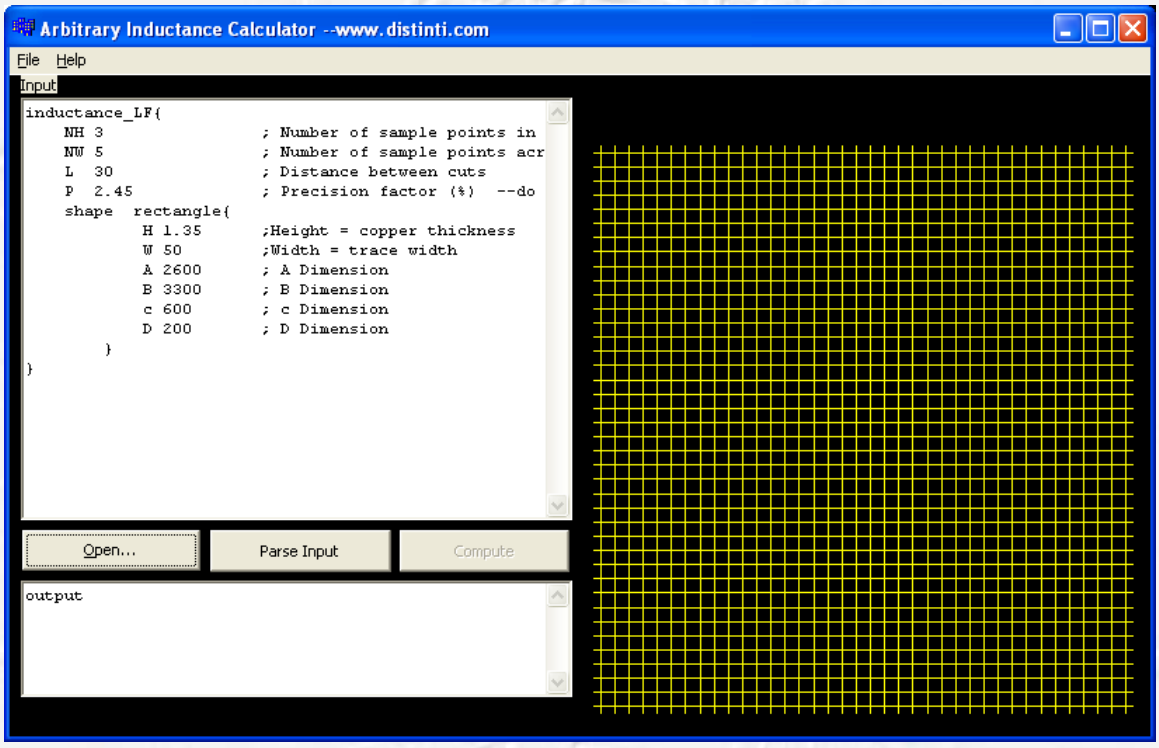
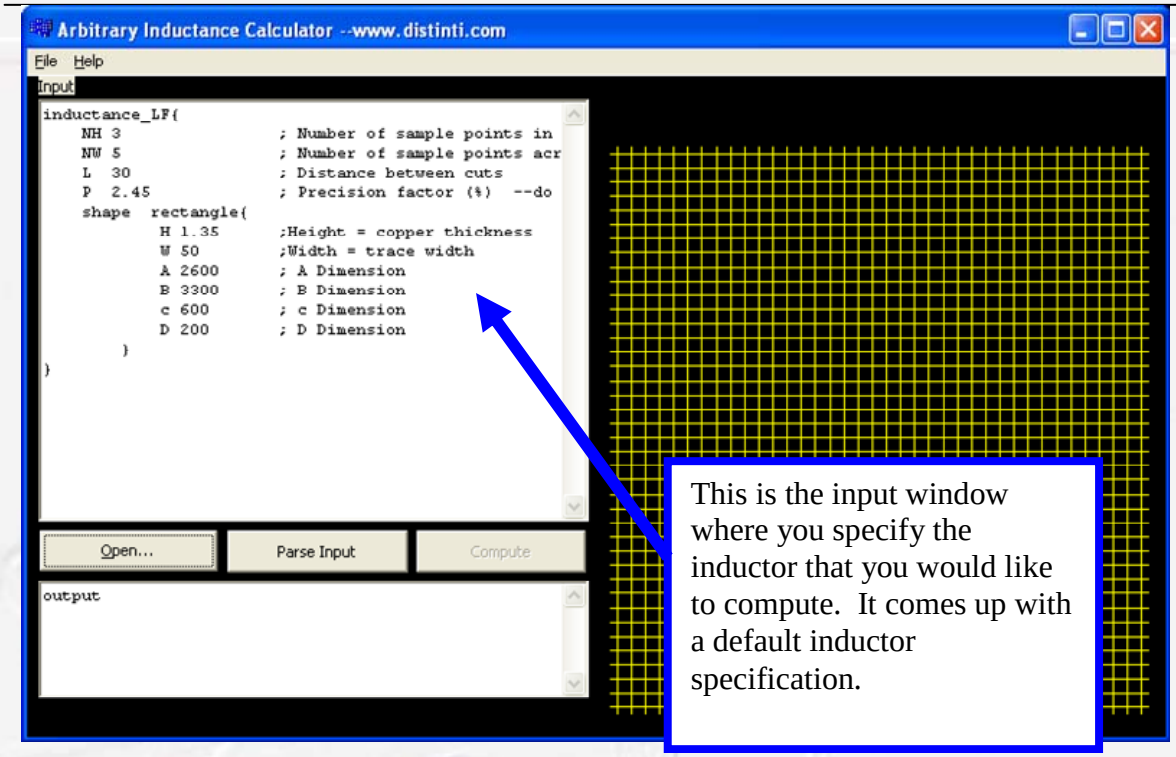
2 Getting Started

2.1 Running the software

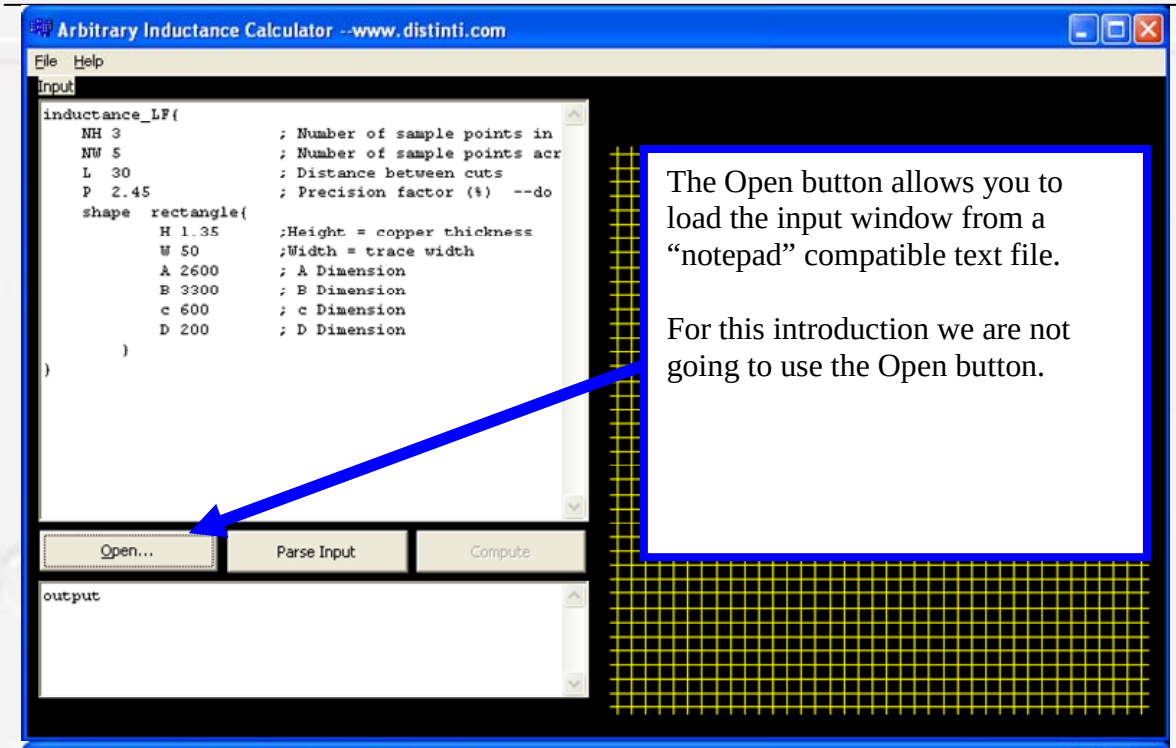
To start the software, double click on the ArbInd.exe file in the directory that you created in the previous section. You should see the following window appear.

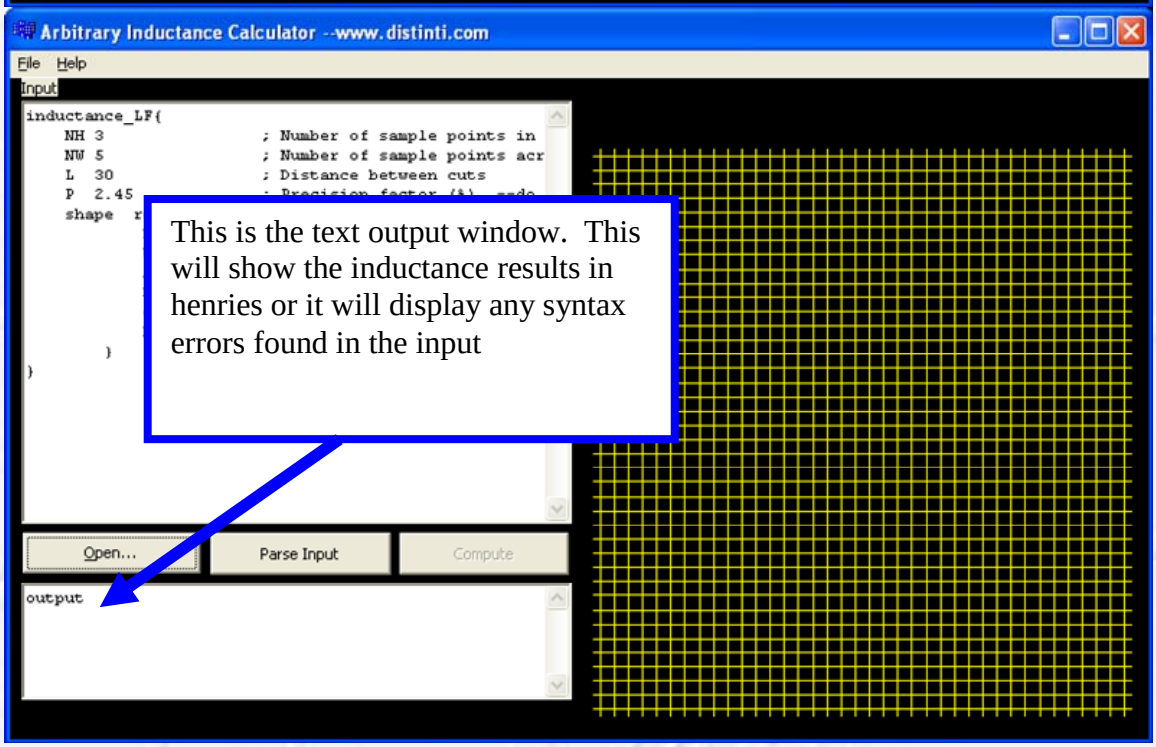


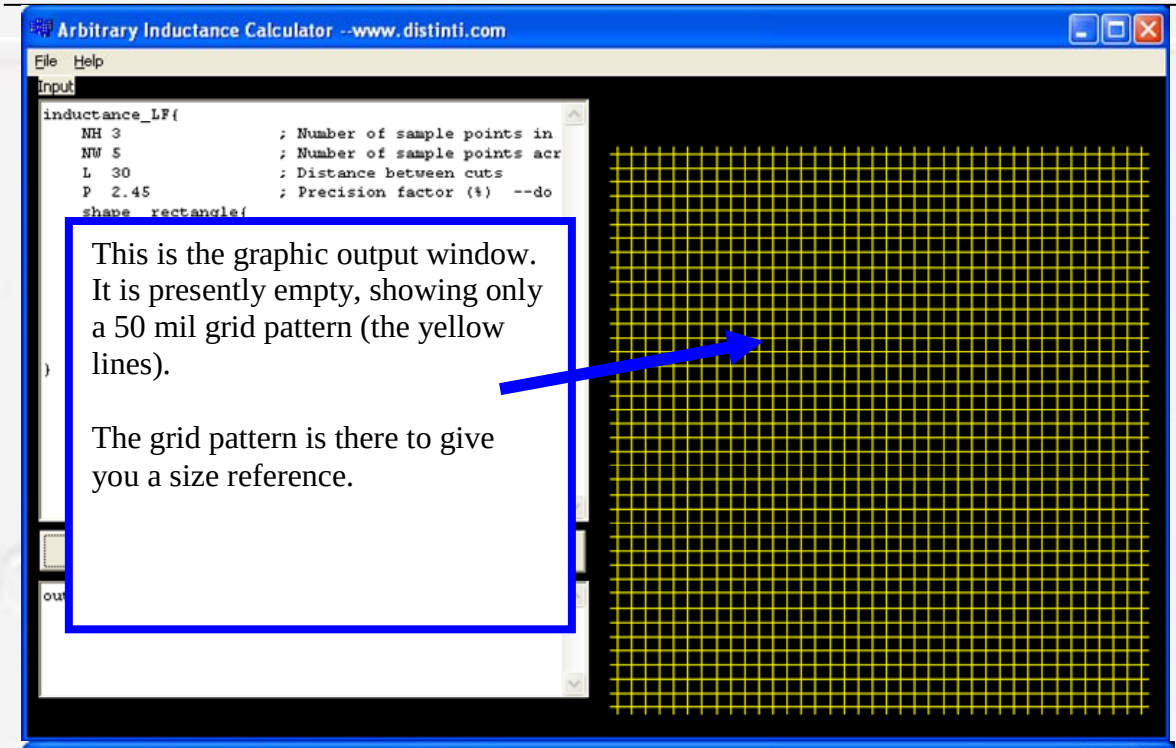
The following screen-shots explain the various elements of the user interface and step through the computation of a basic inductor similar to one from the thesis. It is recommended that you start the software and follow along.

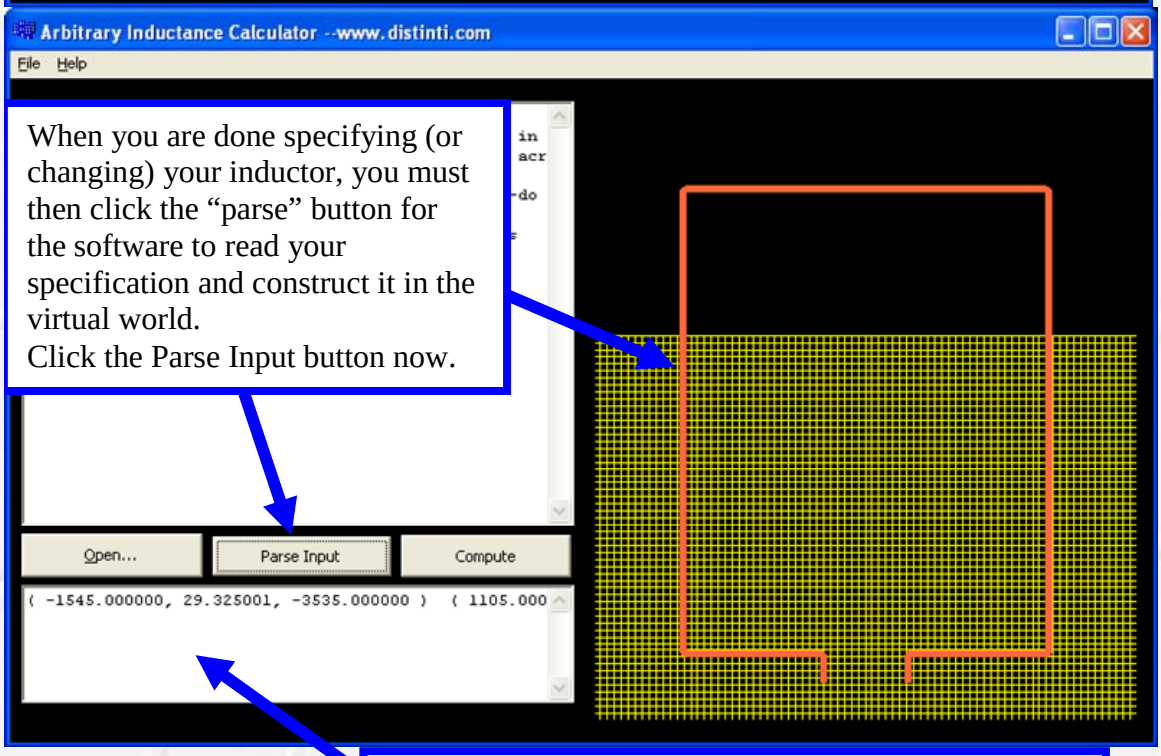


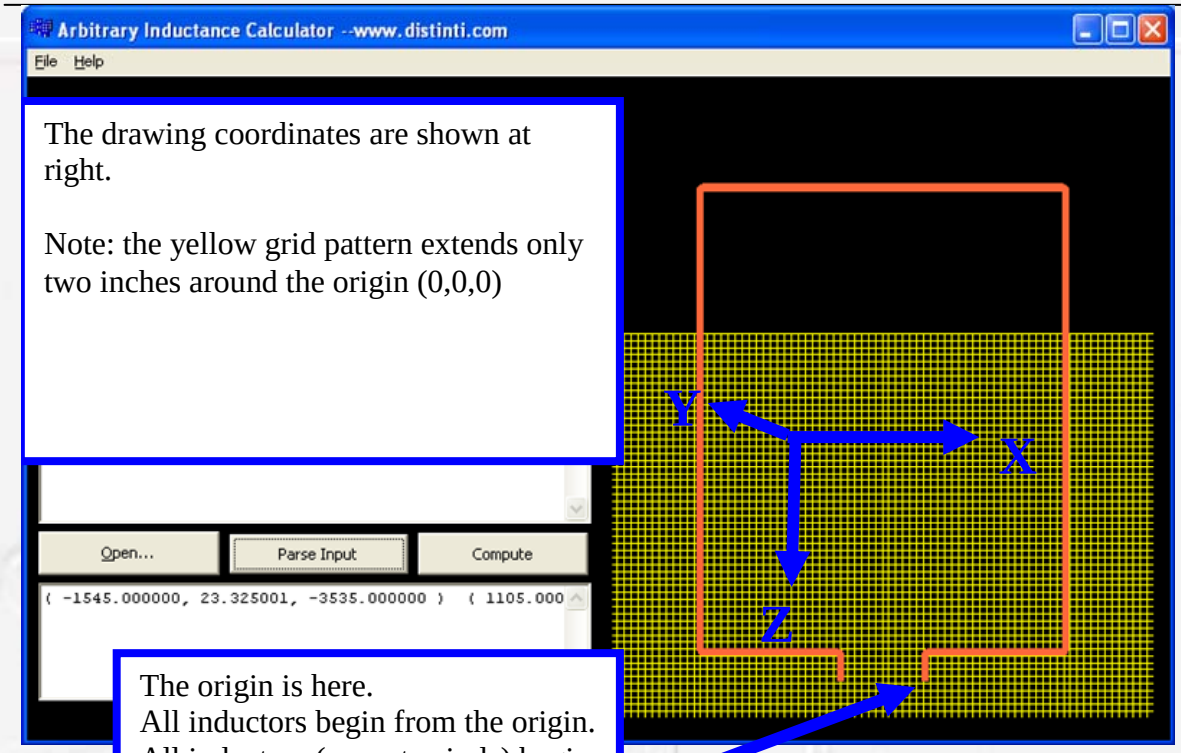
This is the input window where you specify the inductor that you would like to compute. It comes up with a default inductor specification.

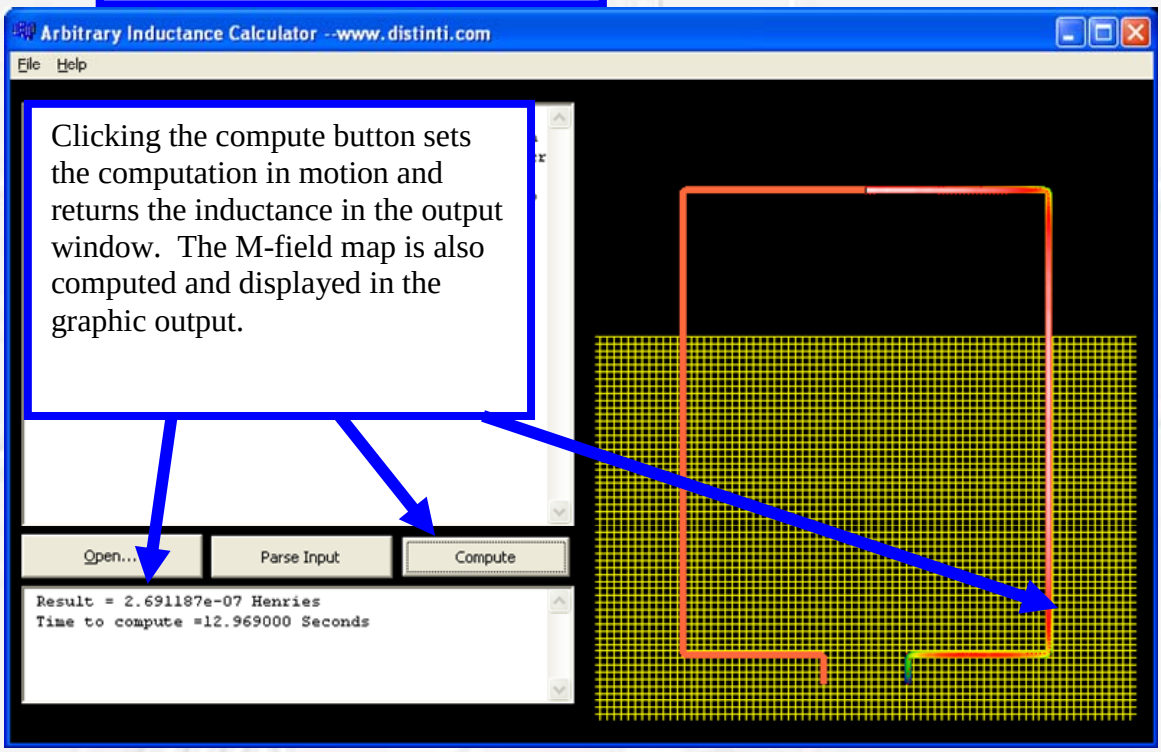

Arbitrary Inductance Calculator --www.distinti.com
File Help
Input
inductance_LF(
NH 3 ; Number of sample points in
NW 5 ; Number of sample points acr
L 30 ; Distance between cuts
P 2.45 ; Precision factor (%) --do
shape rectangle(
H 1.35 ;Height = copper thickness
W 50 ;Width = trace width
A 2600 ; A Dimension
B 3300 ; B Dimension
c 600 ; c Dimension
D 200 ; D Dimension
)
)
Open...
Parse Input
Compute
output
The Open button allows you to load the input window from a "notepad" compatible text file.
For this introduction we are not going to use the Open button.


Arbitrary Inductance Calculator --www.distinti.com
File Help
Input
inductance_LF(
NH 3 ; Number of sample points in
NW 5 ; Number of sample points acr
L 30 ; Distance between cuts
P 2.45
shape r
)
)
Open...
Parse Input
Compute
output
This is the text output window. This will show the inductance results in henries or it will display any syntax errors found in the input


Arbitrary Inductance Calculator --www.distinti.com
File Help
Input
inductance_LF(
NH 3 ; Number of sample points in
NW 5 ; Number of sample points acr
L 30 ; Distance between cuts
P 2.45 ; Precision factor (%) --do
shape rectangle(
This is the graphic output window. It is presently empty, showing only a 50 mil grid pattern (the yellow lines).
The grid pattern is there to give you a size reference.


Arbitrary Inductance Calculator --www.distinti.com
File Help
When you are done specifying (or changing) your inductor, you must then click the "parse" button for the software to read your specification and construct it in the virtual world.
Click the Parse Input button now.
Open...
Parse Input
Compute
(-1545.000000, 29.325001, -3535.000000) (1105.000
The min and max dimension (in mils) are displayed for your reference.


Arbitrary Inductance Calculator --www.distinti.com
File Help
The drawing coordinates are shown at right.
Note: the yellow grid pattern extends only two inches around the origin (0,0,0)
Open...
Parse Input
Compute
(-1545.000000, 23.325001, -3535.000000) (1105.000
Y
X
Z
The origin is here.
All inductors begin from the origin.
All inductors (except spirals) begin drawing toward negative Z.


Arbitrary Inductance Calculator --www.distinti.com
File Help
Clicking the compute button sets the computation in motion and returns the inductance in the output window. The M-field map is also computed and displayed in the graphic output.
Open...
Parse Input
Compute
Result = 2.691187e-07 Henries
Time to compute =12.969000 Seconds

The default inductor results in 269nH. This inductor is experiment #1 from the thesis.

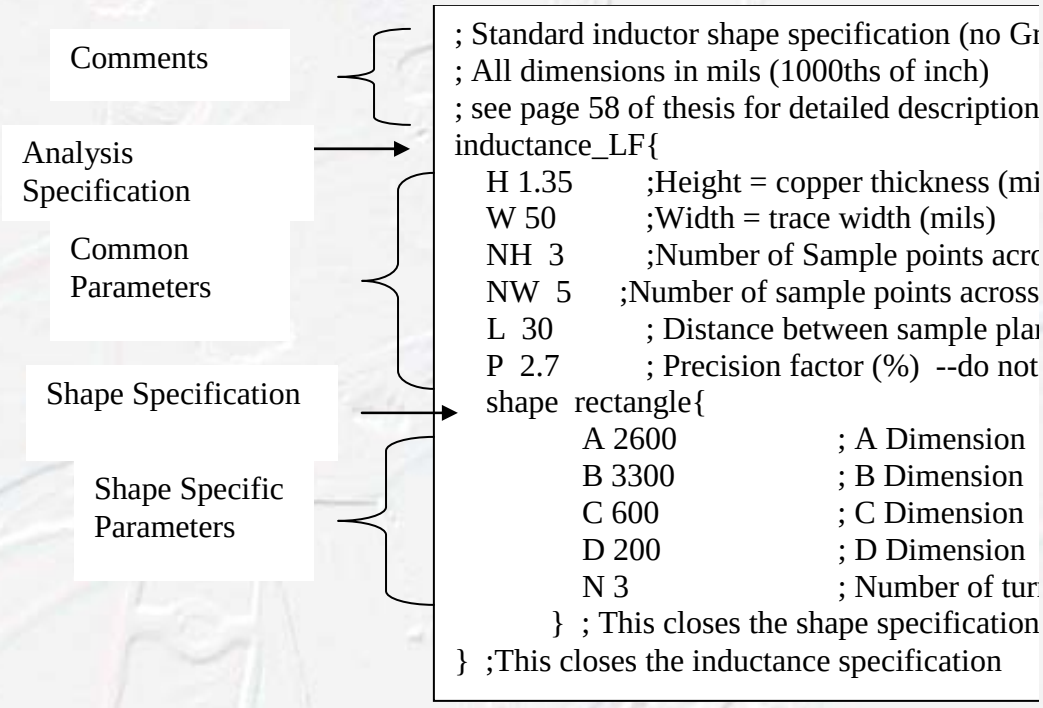
The next sections details the different ways that an inductor can be specified.

3 Specifying a shape

3.1 The Syntax of an Inductance shape specification

The input window is the place to specify the inductor shape to be tested. The text in the input window is parsed by simple text parser that reads the specification and constructs an inductor. You may find it easier to edit these specifications in notepad or some other ANSI compatible text editor. Then cut-and-paste them into the input widow, or open the .txt file using the open button described previously.

The following diagram details the different sections of an inductor specification. These sections are described in more detail in the following paragraphs.


Comments
Analysis Specification
Common Parameters
Shape Specification
Shape Specific Parameters
; Standard inductor shape specification (no Gr
; All dimensions in mils (1000ths of inch)
; see page 58 of thesis for detailed description
inductance_LF{
H 1.35 ;Height = copper thickness (mi
W 50 ;Width = trace width (mils)
NH 3 ;Number of Sample points acr
NW 5 ;Number of sample points across
L 30 ; Distance between sample pla
P 2.7 ; Precision factor (%) --do not
shape rectangle{
A 2600 ; A Dimension
B 3300 ; B Dimension
C 600 ; C Dimension
D 200 ; D Dimension
N 3 ; Number of tur
} ; This closes the shape specification
} ;This closes the inductance specification

3.1.1 Comments

All text following a semicolon (;) to the end of a line is ignored by the text parser. This allows the insertion of comments for human understanding.

3.1.2 Analysis Specification

The only analysis specification that the software presently recognizes is inductance_LF. This stands for low frequency inductance analysis. This line is required.

3.1.3 Common Parameters

The common parameters are independent of the shape of the inductor and typically control the numerical integration and other features. These parameters are described in more detail in section 6.

3.1.4 Shape Specification

The Shape specification section defines the inductor shape. There are 4 built-in shapes (Rectangle, circle, spiral and cspiral (corner lead spiral)); these shapes match those used in my graduate thesis.
There is also an arbitrary shape specification which allows an arbitrary shape to be specified (presently the arbitrary shapes must have same trace width and height through out.)

The shapes are covered in more detail in the sections that follows.

3.1.5 Shape Specific Parameters

These parameters are specific to the shape specified. The parameters are described in the section that follows.

3.2 Built-in Shapes

The 4 built inductors shapes are shown in the following diagram

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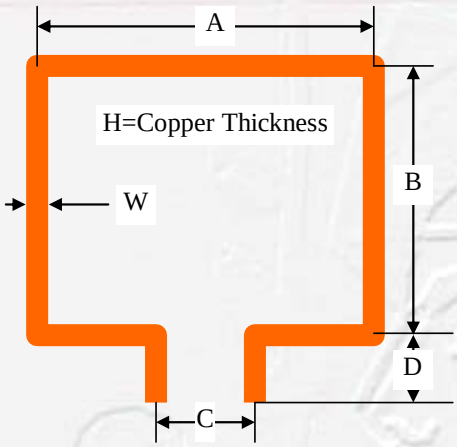
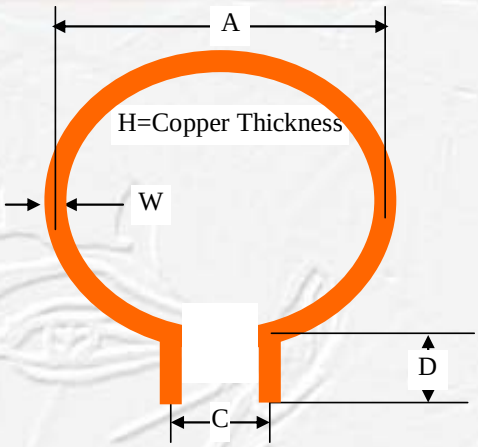
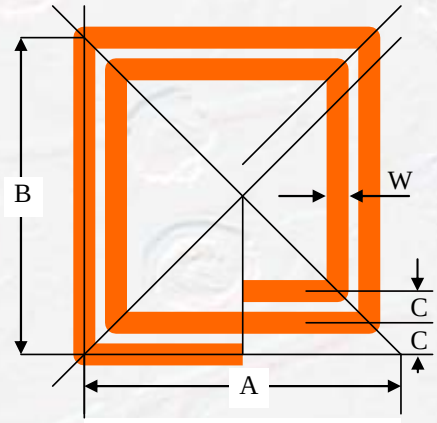
Rectangle



Circle

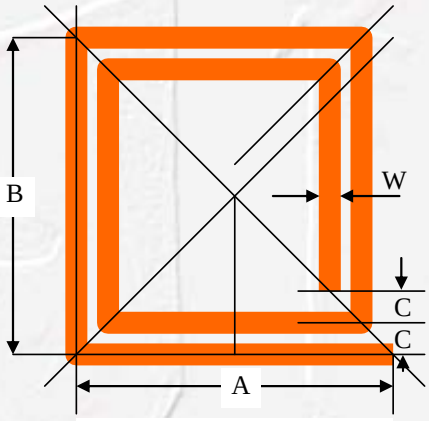


Spiral: Center-lead



H=Copper Thickness
N=Number of turns

Spiral: Corner-lead



H=Copper Thickness
N=Number of turns

The shape codes used in the software are

1) Rectangle
2) Circle
3) Spiral (center lead spiral)
4) CSpiral (corner lead spiral)

The following is an example specification for a rectangular inductor.

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```
; Standard inductor shape specification (no Ground plane)
; All dimensions in mils (1000ths of inch)
inductance_LF{
   H 1.35     ;Height = copper thickness (mils) – 1oz=1.35 2oz=2.7
   W 50       ;Width = trace width (mils)
   NH  3      ;Number of Sample points across the height
   NW  5      ;Number of sample points across the width
   L  30      ; Distance between sample planes (cuts)
   P  2.7     ; Precision factor (%)  --do not make greater than 2.7
   shape  rectangle{
            A 2600          ; A Dimension
            B 3300          ; B Dimension
            C 600           ; C Dimension
            D 200           ; D Dimension
            N 3             ; Number of turns (Spirals only)
         }
}
```

Most of the parameters shows above are self-explanatory; for full details see section 6.

You can cut-and-paste the above text into the input window. You can change the inductor shape by replacing the word “Rectangle” with the appropriate shape code listed above.

3.3 Arbitrary Shapes

This software also allows the specification of an arbitrary shape. The shape code used for an arbitrary inductor is “Arbitrary”. Inside the brackets (see example below) list as many “Straight”, “Left” or “Right” segments as desired (the total number of segments must be an odd number for best results).

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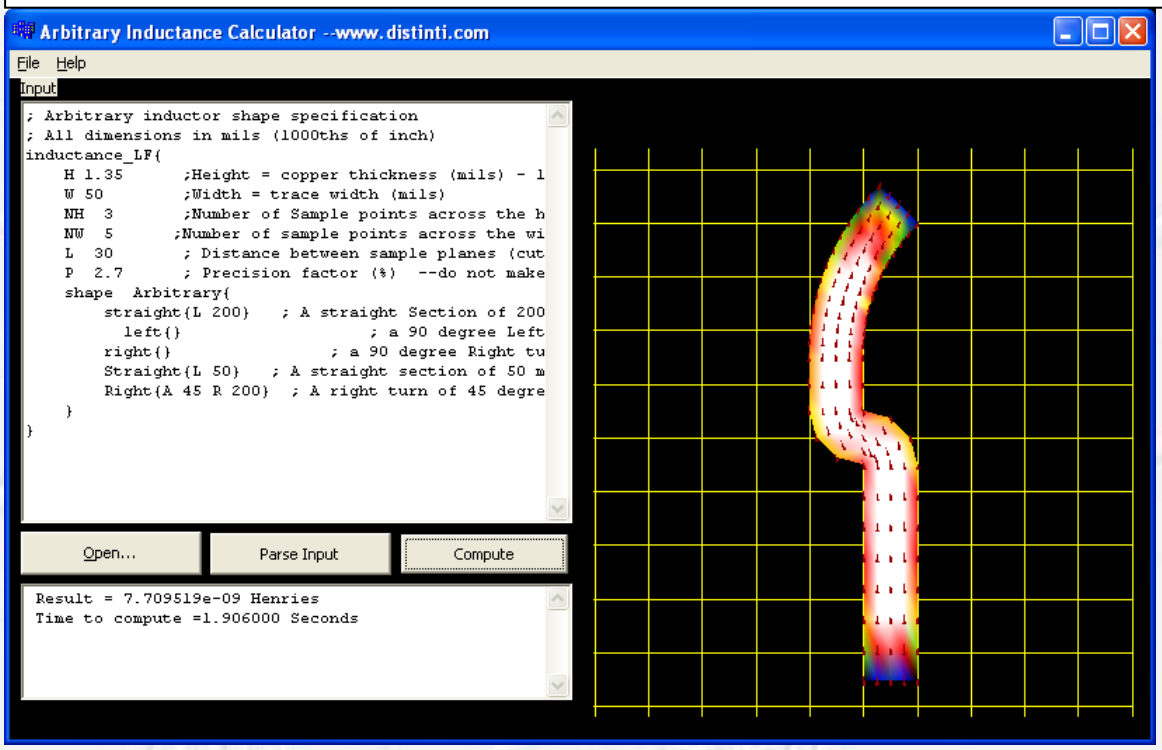
```
; Arbitrary inductor shape specification
; All dimensions in mils (1000ths of inch)
inductance_LF{
   H 1.35     ;Height = copper thickness (mils) – 1oz=1.35 2oz=2.7
   W 50       ;Width = trace width (mils)
   NH  3      ;Number of Sample points across the height
   NW  5      ;Number of sample points across the width
   L  30      ; Distance between sample planes (cuts)
   P  2.7     ; Precision factor (%)  --do not make greater than 2.7
   shape  Arbitrary{
        straight{L 200}   ; A straight Section of 200 mils
        left{}            ; a 90 degree Left turn of radius W*0.51
        right{}           ; a 90 degree Right turns
        Straight{L 50}    ; A straight section of 50 mils length
        Right{A 45 R 200}  ; A right turn of 45 degrees with radius 200 mils

   }
}
```


Arbitrary Inductance Calculator --www.distinti.com
File Help
Input
; Arbitrary inductor shape specification
; All dimensions in mils (1000ths of inch)
inductance_LF{
H 1.35 ;Height = copper thickness (mils) - 1
W 50 ;Width = trace width (mils)
NH 3 ;Number of Sample points across the h
NW 5 ;Number of sample points across the wi
L 30 ; Distance between sample planes (cut
P 2.7 ; Precision factor (%) --do not make
shape Arbitrary{
straight{L 200} ; A straight Section of 200
left{} ; a 90 degree Left
right{} ; a 90 degree Right tu
Straight{L 50} ; A straight section of 50 m
Right{A 45 R 200} ; A right turn of 45 degre
}
}
Open...
Parse Input
Compute
Result = 7.709519e-09 Henries
Time to compute =1.906000 Seconds

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3.3.1 Straight Segments

A straight segment must specify a Length in mils using one of the syntax styles shown below.

Straight {L=100} ; the equal sign is not necessary

```
Straight {
        L 100
}
```

There is a lot of flexibility in the text parser; you can try different styles that suite your tastes.

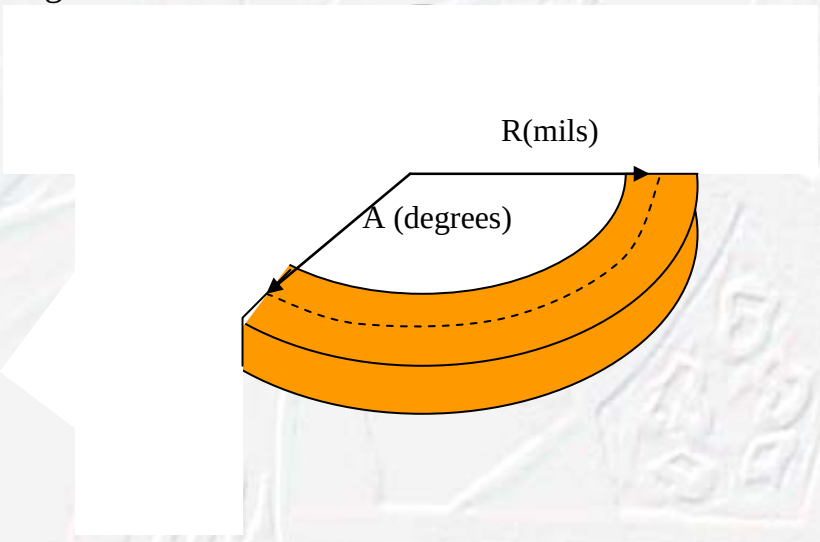
3.3.2 Left/Right Segments

The Left and Right segments allow you specify circular segments or corners of rectangular inductors.

The Left and Right Segments require two parameters. The parameters are Angle (A) and Radius (R).

The Angle "A" specifies what angle (in degrees) of arc the turn will advance through. The default angle is 90 degrees is "A" is not specified.

The Radius (R) specifies the radius of the arc in mils. See following diagram.



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R specifies the Radius to the centerline of the trace (W/2). R defaults to W*0.51 if not specified. The software will not let you set R to less than W/2.

The length of the arc is found with the following equation

$$L(arc) = \frac{\pi RA}{180}$$ (Length through centerline of arc)

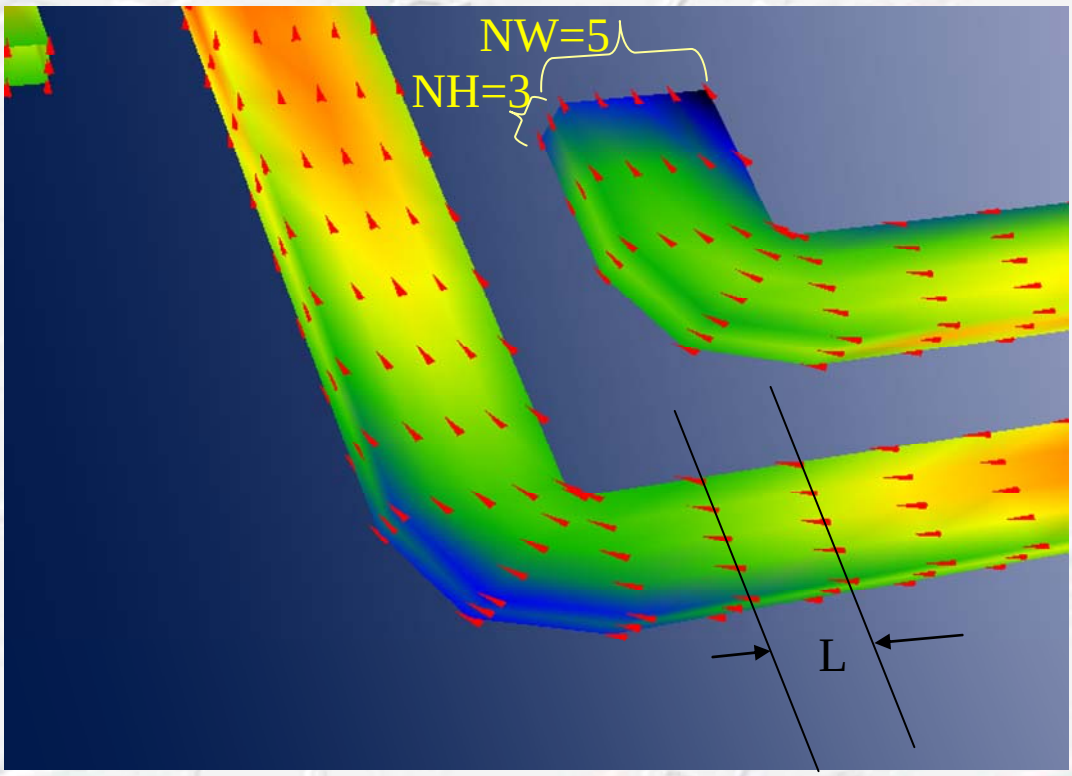
3.3.3 Important consideration when using Arbitrary Inductor.

The number of segments should always be odd. The reason for this is found in section 4.1.1.

4 Sampling and Precision Specification

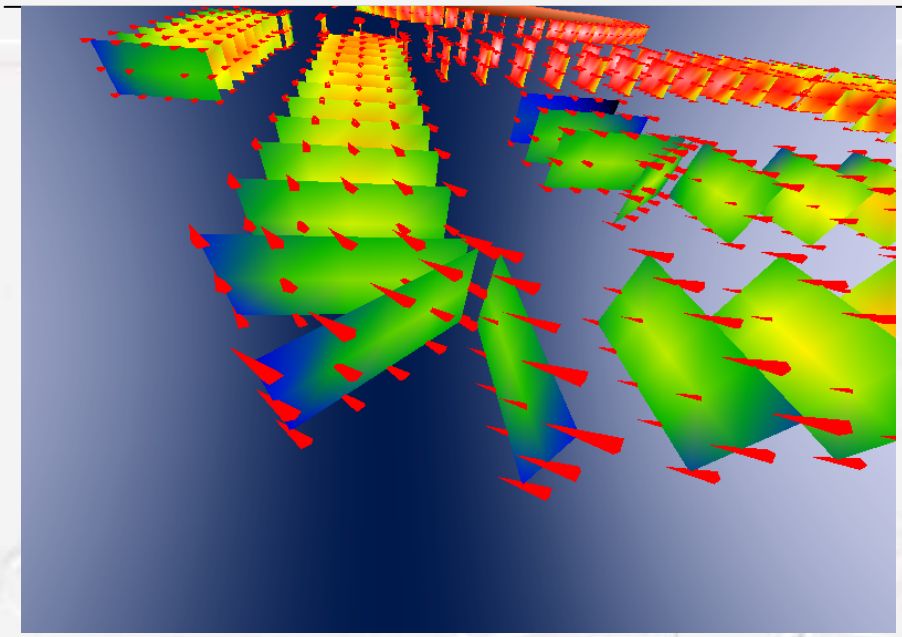
The sampling specification consists of 3 parameters (NW, NH and L) and the Precision specification consists of 1 parameter (P).

The sampling specification details the density of the M-field map (see graduate thesis). The M-field is evaluate at NW points along the width of the inductor and NH points along the height of the inductor (see the following diagram)



These NW x NH sets of samples form what are called “Sample planes” (see next diagram). These sample planes are spaced along the length of the inductor by L mils.

L is not absolute. The algorithm will adjust L on a segment by segment basis to



The red arrows show the points where the M-field is evaluated. The color map shows the intensity of the field (interpolated between the points) and the direction of red arrows show the direction of the field. The color map normalizes white to the peak M-field sample point of the inductor under test (IUT) and black to the min M-field sample point of the IUT. The same color shown on two different IUT plots does NOT means that the M-Fields are the same.

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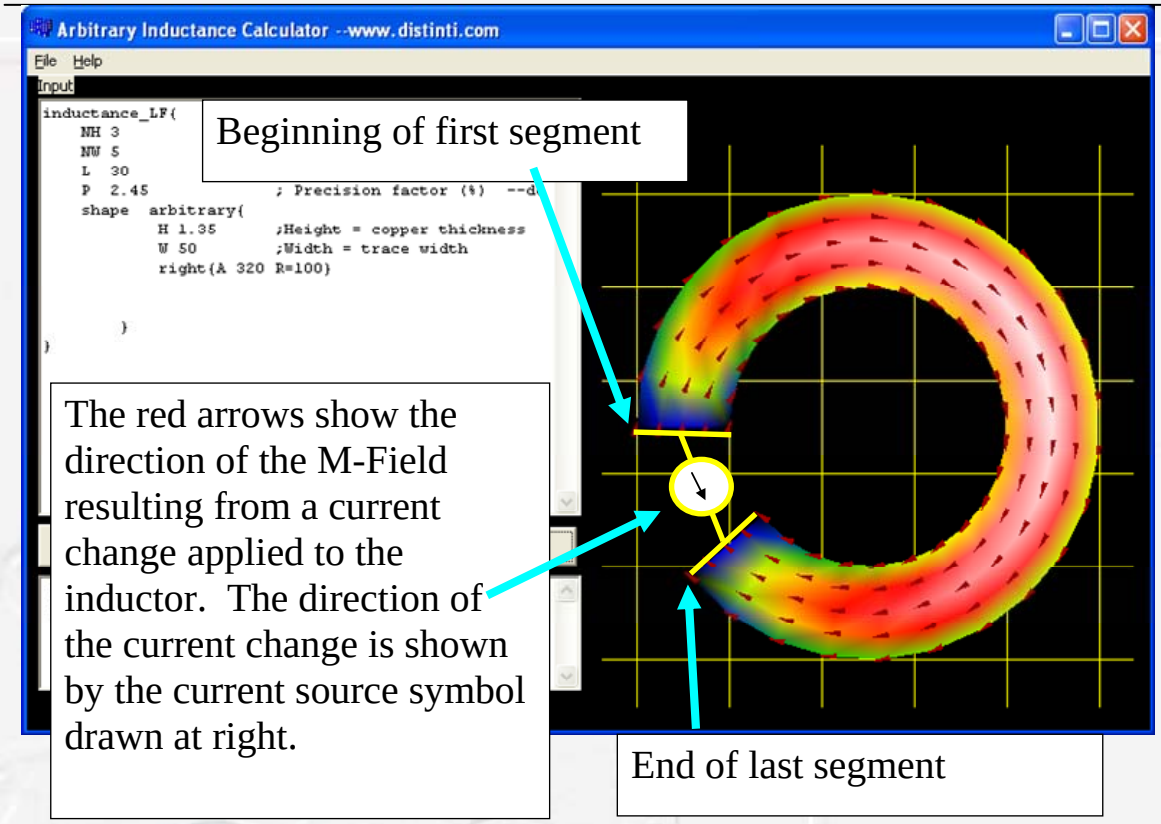

Arbitrary Inductance Calculator --www.distinti.com
File Help
Input
inductance_LF{
NH 3
NW 5
L 30
P 2.45 ; Precision factor (%) --d
shape arbitrary{
H 1.35 ;Height = copper thickness
W 50 ;Width = trace width
right{A 320 R=100}
}
}
Beginning of first segment
The red arrows show the direction of the M-Field resulting from a current change applied to the inductor. The direction of the current change is shown by the current source symbol drawn at right.
End of last segment

Figure 1: The applied current change which results in shown M-Field directions (red-arrows)

Naturally, the accuracy of the inductance calculation improves as the number of sample points increase (by increasing NW,NH and decreasing L); however, like many numerical algorithms the time to compute the results increases.

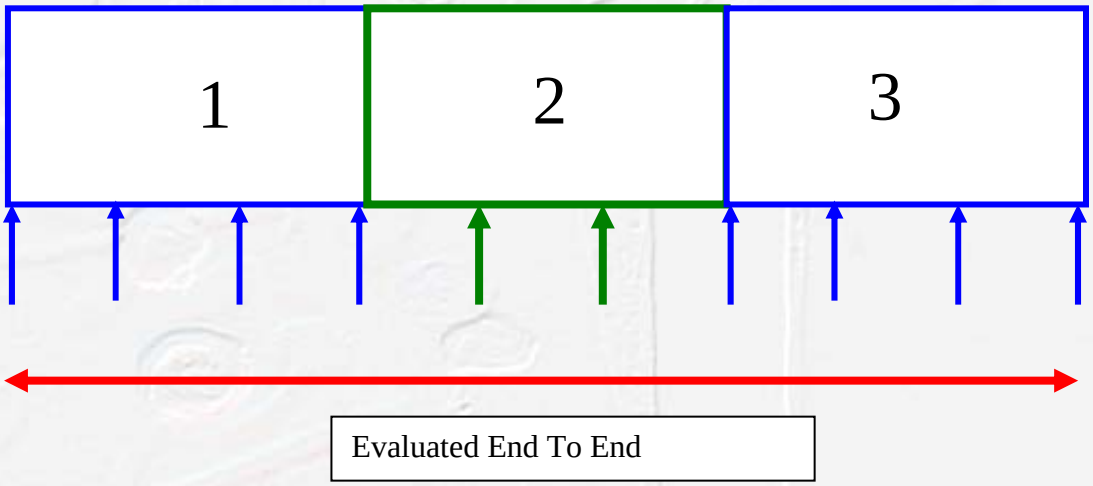
From experience I have found that for the printed circuits tested in the thesis, the NW=5, NH=3, L=30 are sufficient to achieve results to within 1% of convergence. The term "1% convergence" means that the result from using these values is within 1% of the best possible numerical result obtainable.

There is an Excel Spread sheet (convergence.xls) that shows multiple runs done with varying parameters detailing the effect on convergence and computation time. This spreadsheet should be found in the same location that this file is found.

4.1.1 L and Even/Odd segments

In order to optimize sample plane spacing, even and odd segments are treated differently. Odd segments (see blue sections below) have the sample planes (represented by arrows) evenly spaced from end to end. In order "dove-tail" the segments and prevent inefficient duplication of samples planes, the even segments (green) omit the sample planes at the ends of the segment.

The algorithm will reduce L as needed in order to fit the sample planes into a given segment for the purpose of achieving the desired "dove-tailing."



Note: this diagram shows three straight segments as an example. This sampling scheme applies to any combination of segment types.

The AIA evaluates the inductance of a structure between the first and last sample planes. If you specify an even number of segments the evaluation of the inductance will not be complete since the "end" sample plane will be missing (shown in the next diagram). **Thus it is recommended that the number of segments be odd.**

The next example shows what happens when an even number of segments are specified.

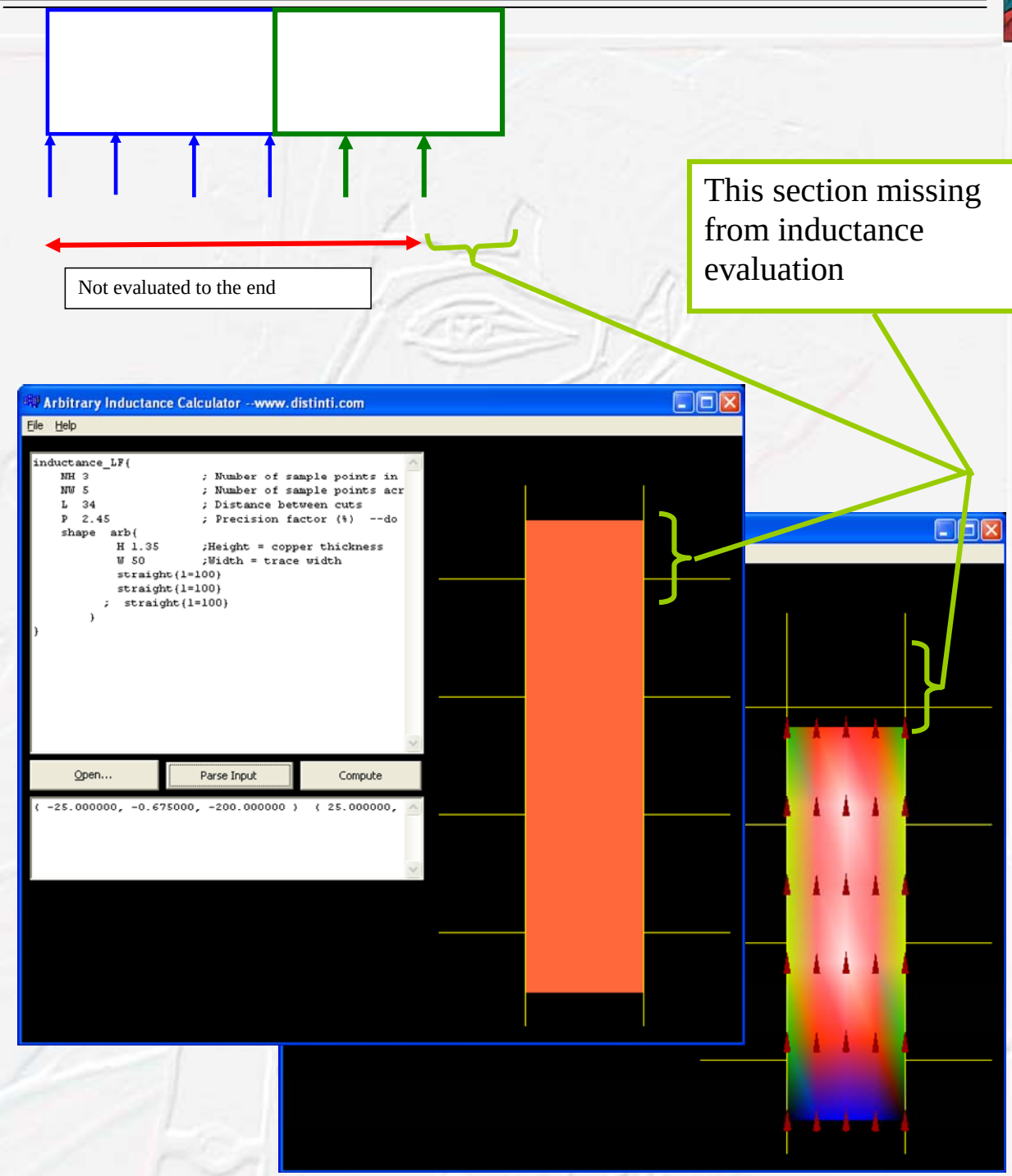
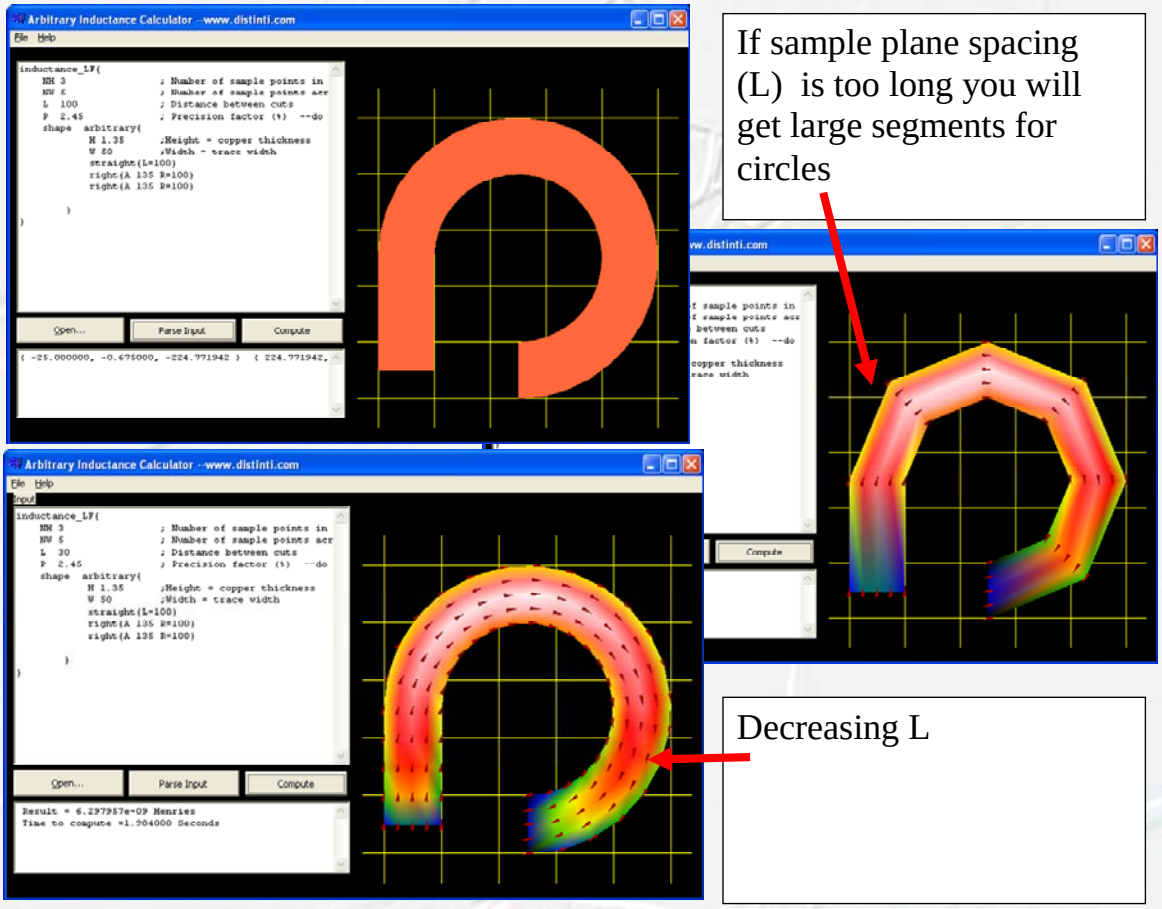


Figure 2: Even Segments cause data truncation

There are a number of techniques to ensure that the number of segments is odd. The simplest method is to divide an existing segment in two.

4.1.2 Check sample plane spacing for circular segments

After computing a circular segments (Right/Left or Arbitrary); check the output graphic to ensure that the curves are not too segmented. If they are, then decrease L.



4.1.3 The Precision Factor P

The Precision Factor is a key parameter for the adaptive integration algorithm (AIA). I can not divulge the true meaning of the Precision Factor due to the proprietary nature of the adaptive algorithm; however, I can give you enough information to use it effectively.

Analysis of the AIA teaches us that it becomes unstable for values of P>2.7. This is confirmed in the following convergence graph which shows the computed inductance (normalized to 100%) as the value of P changes.

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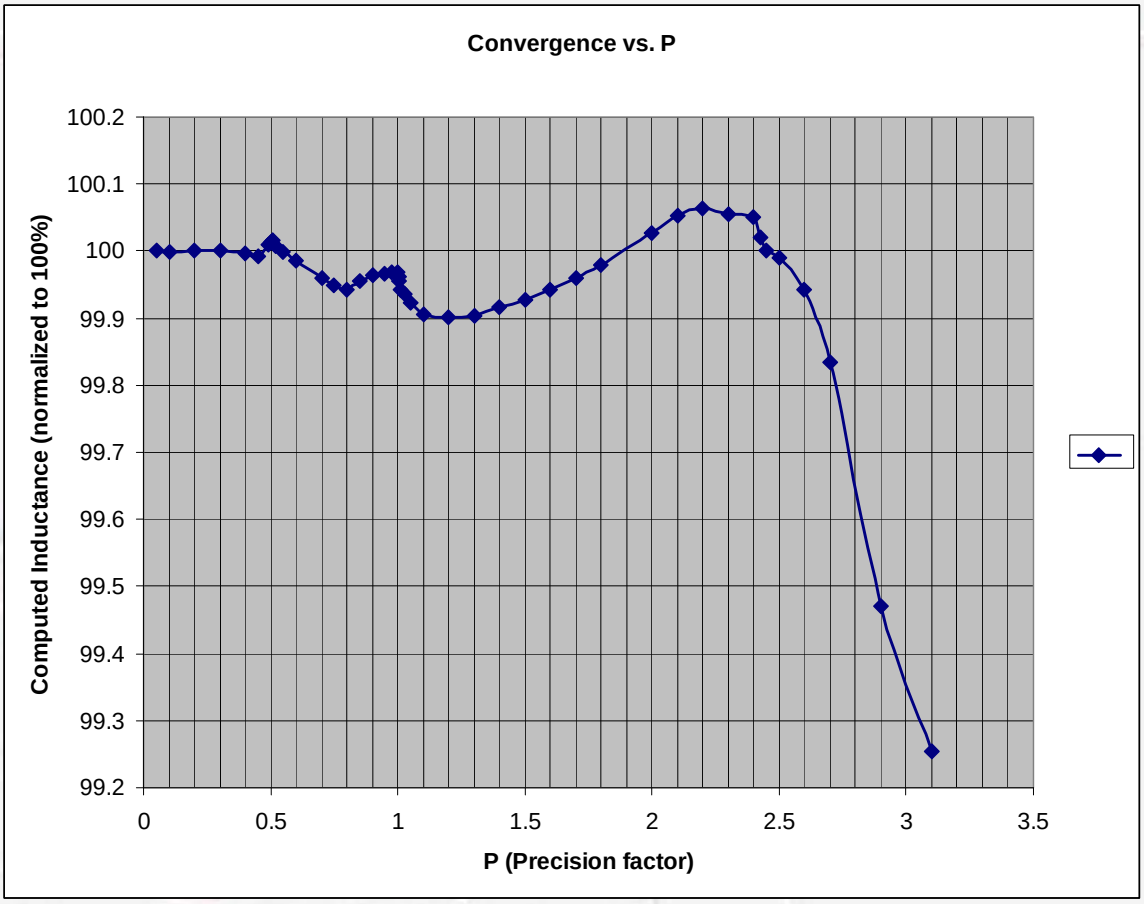
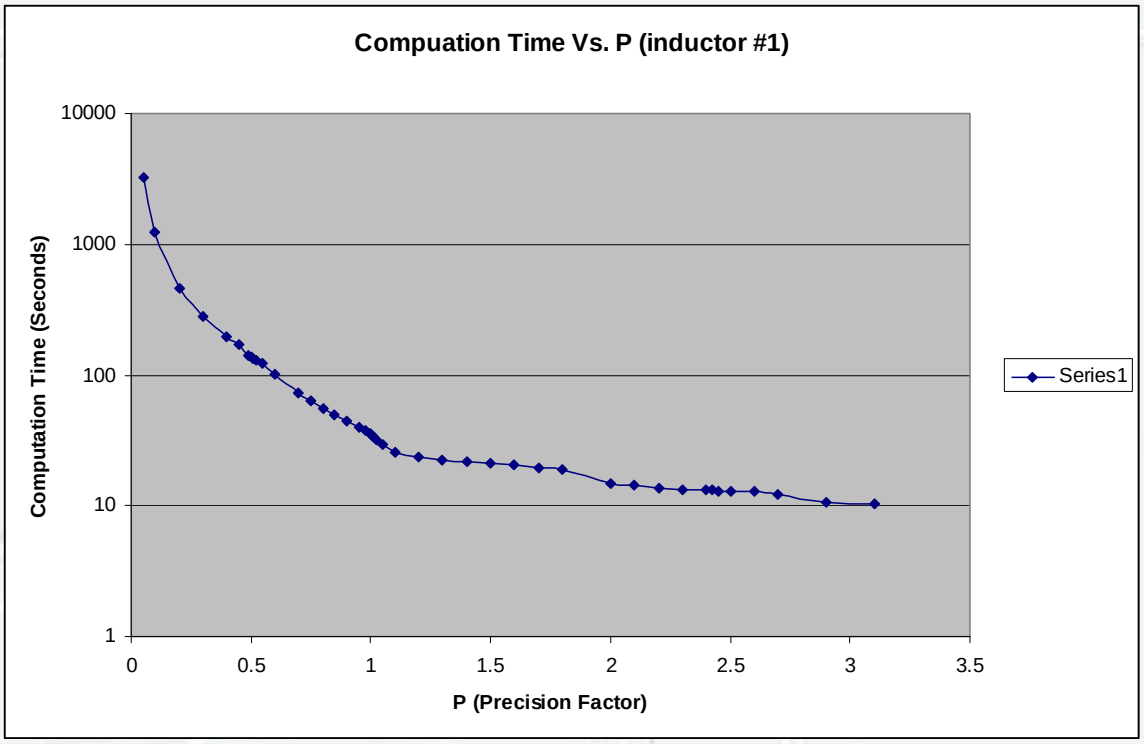


The chart shows that the computed results will be within 0.1% convergence for values of P less than 2.6. Above 2.7 the algorithm quickly degrades as predicted by analysis.

All of the thesis data was calculated with P=1.

The value of P=2.45 is sufficient for any real world application.

The effect of P on computation time is shown in the following graph.



Both of the above charts use Thesis inductor #1. This inductor comes up as the default test in the input windows when the application is started.

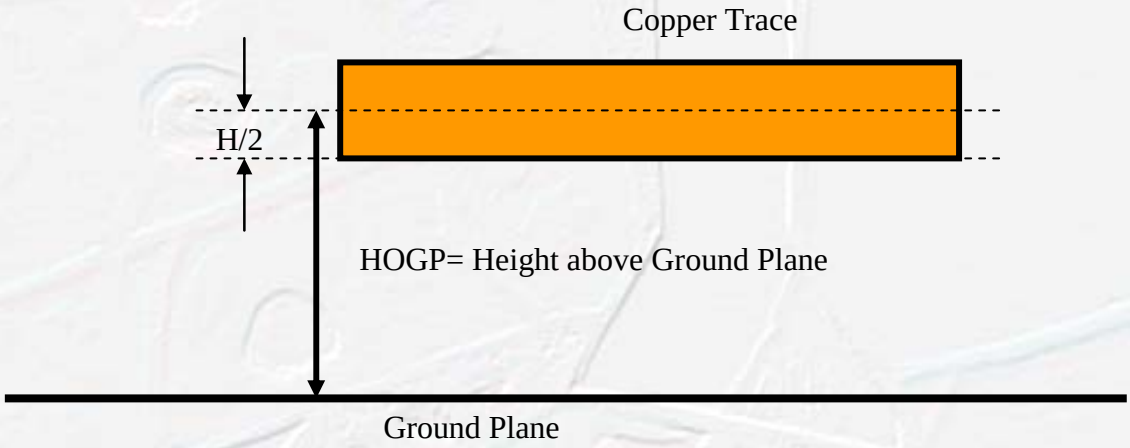
5 Ground Planes

PC traces are typically layered next to, or between, conducting copper planes. These conducting planes significantly affect the measured inductance (see my graduate thesis for details) and therefore need to be considered. Although the term "Ground plane" is used, these planes do not need to be connected to any potential.

5.1 Single Ground Planes

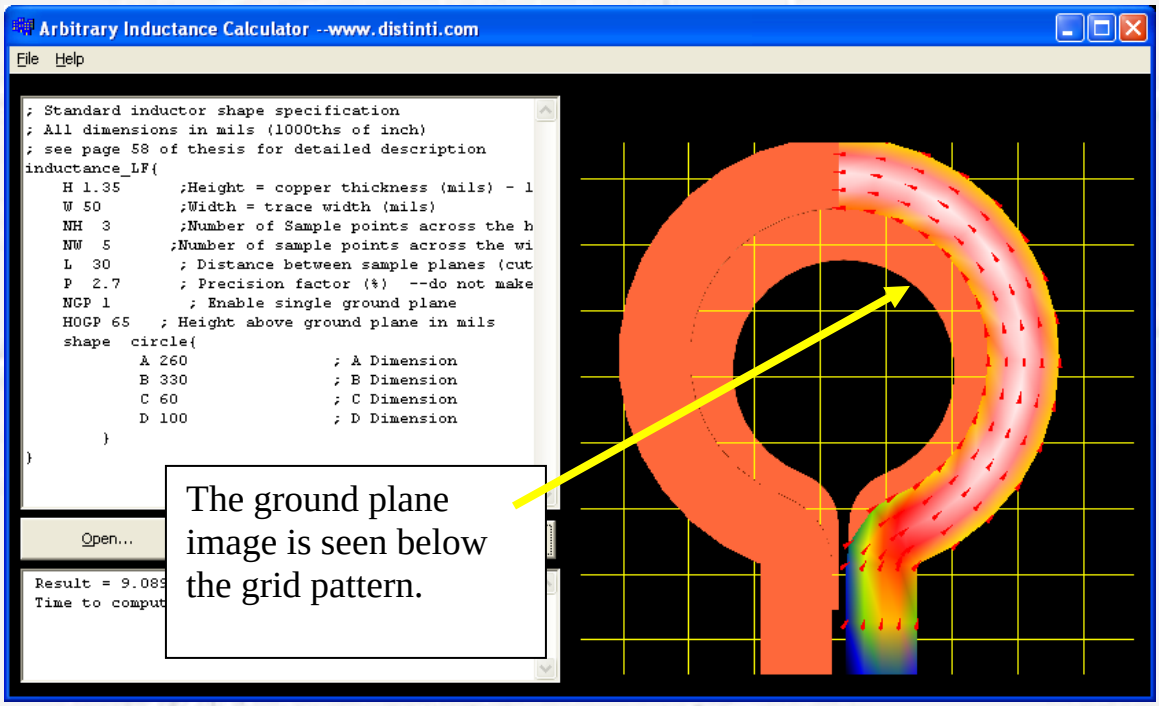
To specify a single ground plane, only two parameters need to be added to the common parameter section.

NGP 1 ; Enable single ground plane
HOGP 65 ; Height above ground plane in mils



Example

```
; Standard inductor shape specification
; All dimensions in mils (1000ths of inch)
; see page 58 of thesis for detailed description
inductance_LF{
    H 1.35      ;Height = copper thickness (mils) - 1oz=1.35 2oz=2.7
    W 50        ;Width = trace width (mils)
    NH  3       ;Number of Sample points across the height
    NW  5       ;Number of sample points across the width
    L  30       ; Distance between sample planes (cuts)
    P  2.7      ; Precision factor (%)  --do not make greater than 2.7
    NGP 1         ; Enable single ground plane
    HOGP 65   ; Height above ground plane in mils
    shape  circle{
            A 260               ; A Dimension
            B 330               ; B Dimension
            C 60                ; C Dimension
            D 100               ; D Dimension
        }
}
```



5.2 Dual Ground Planes

To specify a dual ground plane, three parameters need to be added to the common parameters section of the specification. These are:

```
NGP 2       ; Enable dual ground plane
HOGP 65   ; Height above ground plane in mils
NGPI 10     ; Number of Ground plane image pairs
```

If NGPI is not specified, it defaults to 70 image pairs. For description of the meaning of "number of ground plane images pairs", see my graduate thesis. Note: NGPI is only meaningful if NGP = 2; it is ignored for other values of NGP.

```
; Standard inductor shape specification
; All dimensions in mils (1000ths of inch)
; see page 58 of thesis for detailed description
inductance_LF{
   H 1.35    ;Height = copper thickness (mils) - 1oz=1.35 2oz=2.7
   W 50      ;Width = trace width (mils)
   NH  3     ;Number of Sample points across the height
   NW  5     ;Number of sample points across the width
   L  30     ; Distance between sample planes (cuts)
   P  2.7    ; Precision factor (%)  --do not make greater than 2.7
   NGP 2     ; Enable dual ground plane
   NGPI 4    ;limit to 4 image pairs (70 is default)
   HOGP 65   ; Height above ground plane in mils
   shape  circle{
            A 260              ; A Dimension
            B 330              ; B Dimension
            C 60               ; C Dimension
            D 100              ; D Dimension
         }
}
```

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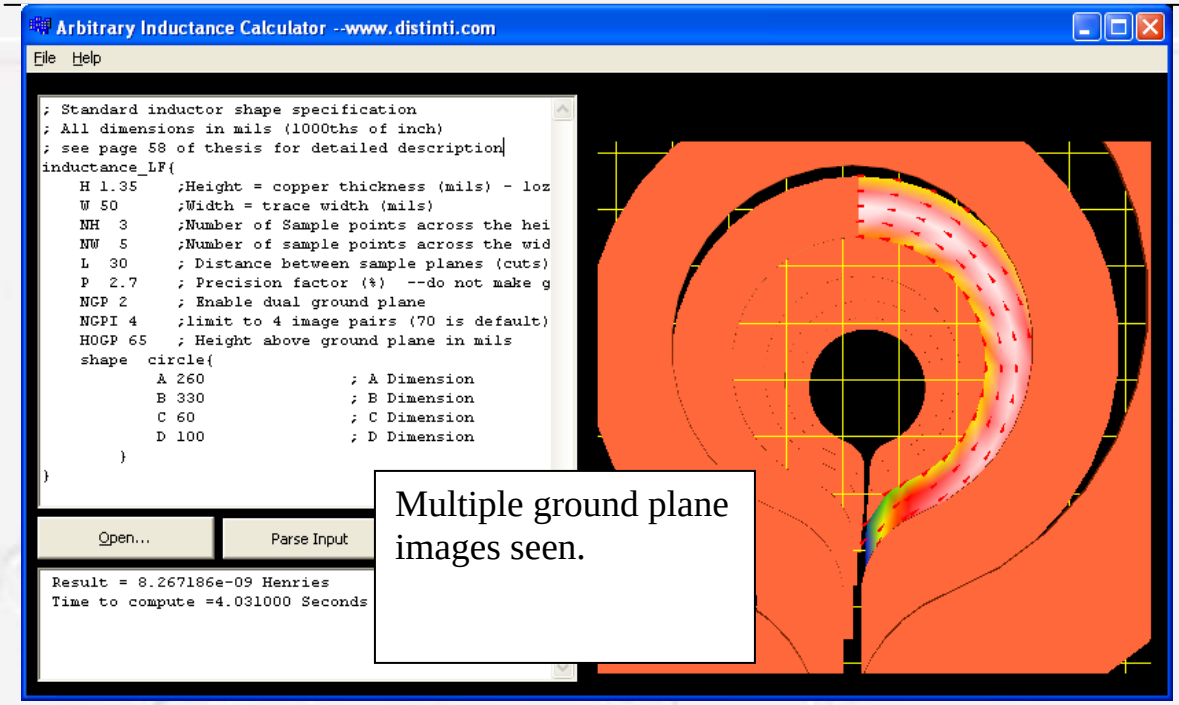
Arbitrary Inductance Calculator --www.distinti.com
File Help
; Standard inductor shape specification
; All dimensions in mils (1000ths of inch)
; see page 58 of thesis for detailed description
inductance_LF{
H 1.35 ;Height = copper thickness (mils) - loz
W 50 ;Width = trace width (mils)
NH 3 ;Number of Sample points across the hei
NW 5 ;Number of sample points across the wid
L 30 ; Distance between sample planes (cuts)
P 2.7 ; Precision factor (%) --do not make g
NGP 2 ; Enable dual ground plane
NGPI 4 ;limit to 4 image pairs (70 is default)
HOGP 65 ; Height above ground plane in mils
shape circle{
A 260 ; A Dimension
B 330 ; B Dimension
C 60 ; C Dimension
D 100 ; D Dimension
}
}
Open...
Parse Input
Result = 8.267186e-09 Henries
Time to compute =4.031000 Seconds
Multiple ground plane images seen.

6 Parameters

This section gives detailed description of the parameters used to specify an inductor.

6.1 A

The parameters A is used differently depending upon the shape selected. For “built-in” shapes, “A” represents dimension A of the “Built-in” shapes. See section 3.2 for a list of the built in shapes.

For Arbitrary Shapes, “A” represents the angle (in degrees) through which a “Right turn” or “Left turn” will progress (see section 3.3.2)

6.2 B, C, D, N

These are “Built-in” shape specific parameters. Please see section 3.2 for their meaning.

6.3 H

H is the trace height in mils. Use 1.35 for 1oz copper and 2.7 for 2 oz copper.

6.4 HOGP

HOGP is height above ground plane. This is the distance from the surface of the ground plane to the centerline of the trace.

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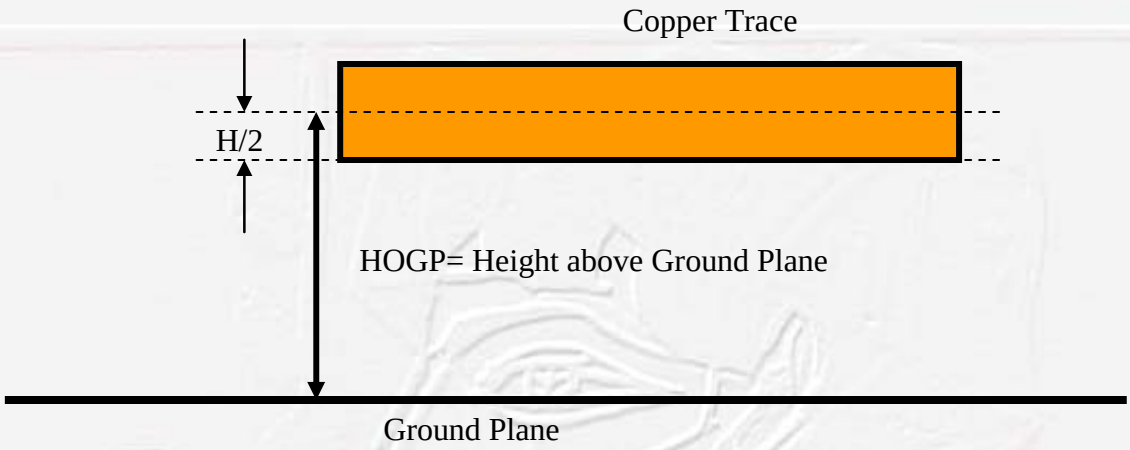


This value is ignored if the parameter NGP=0

For dual ground planes (NGP=2), the following diagram represents

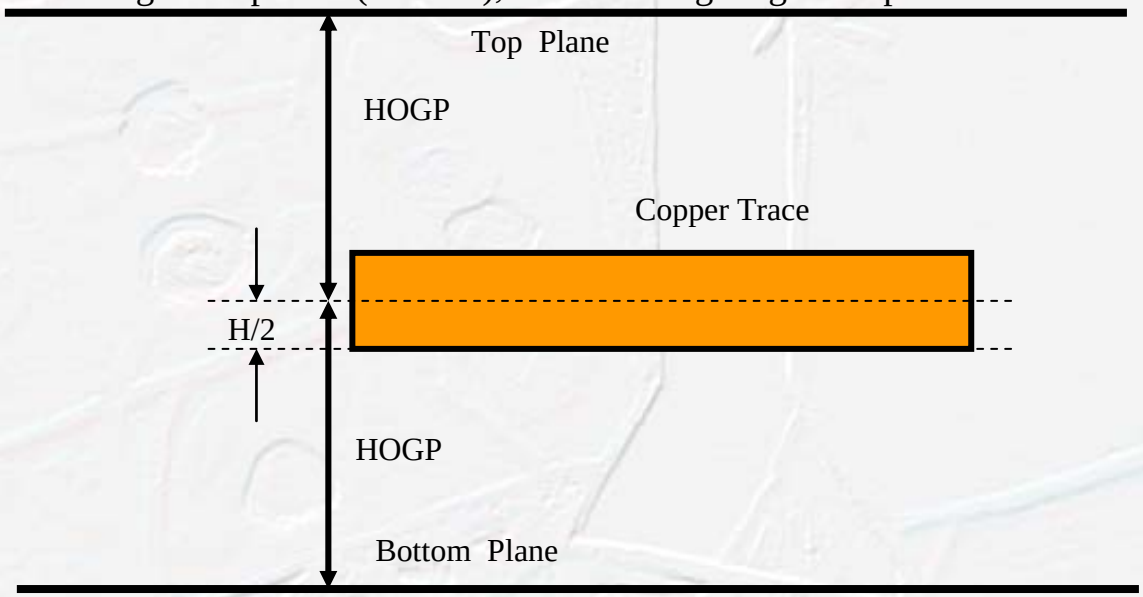
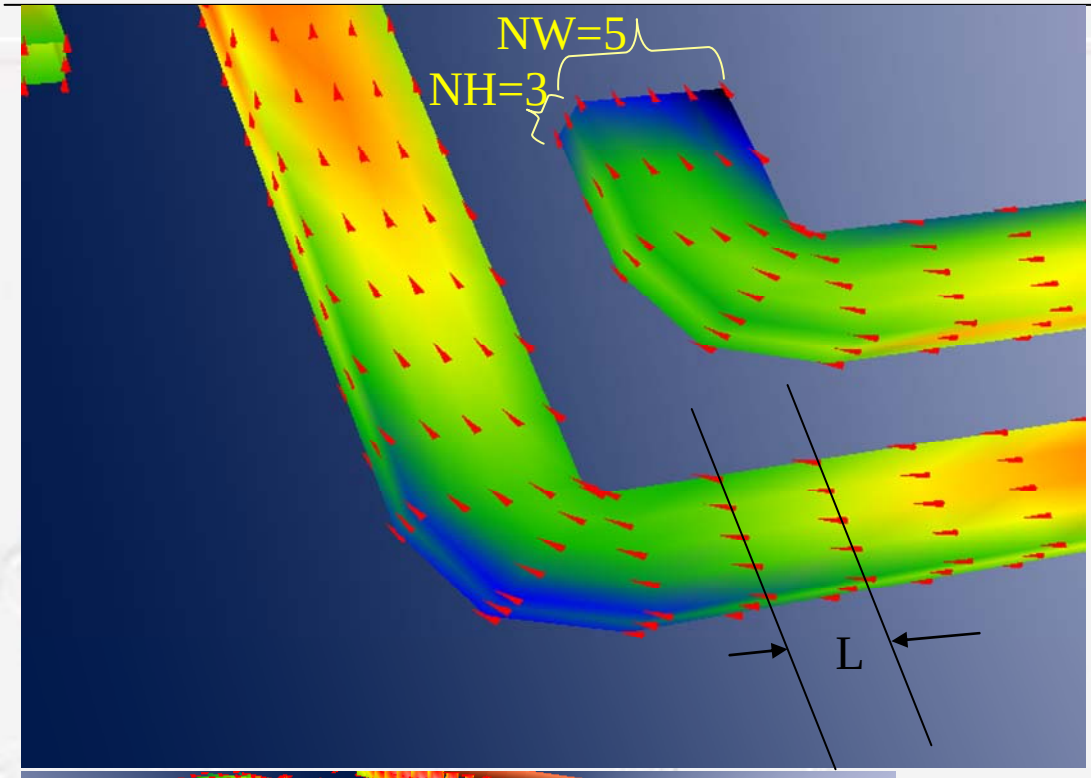
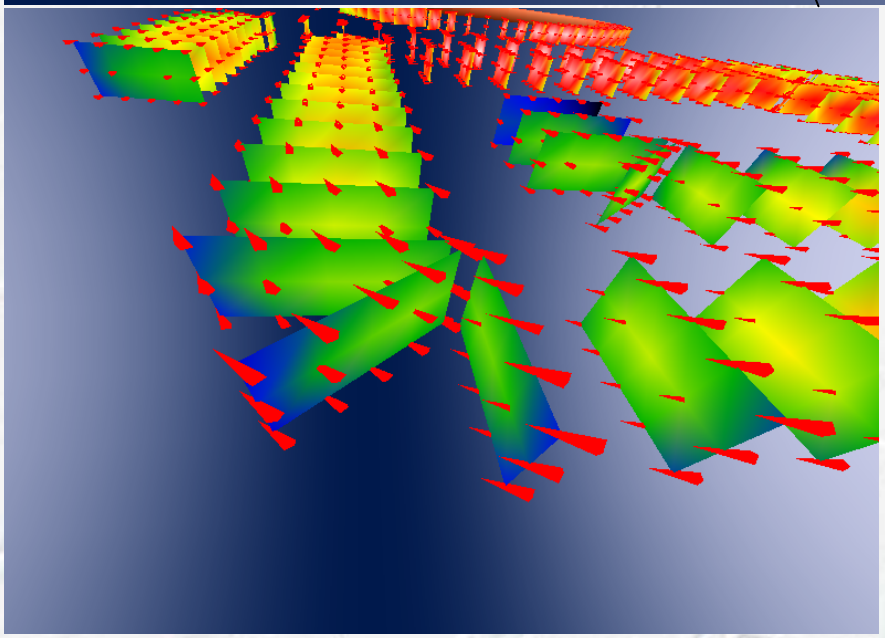


Figure 3: Dual Ground Plane configuration

6.5 L

"L" has two uses. For Arbitrary inductors, it specifies the length in mils of the straight segments.
In the common parameters block, "L" specifies the maximum distance between sampling planes. The algorithm may use slight smaller values of L in order to optimize the "dove-tailing" between segments. See section 4.1.1





6.6 P (Precision Factor)

See Section 4.1.3

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6.7 NGP

Number of ground planes.
NGP=0 for no ground planes
NGP=1 for single ground planes
NGP>=2 for Dual Ground planes

6.8 NGPI

Number of Ground Plane Image Pairs. When considering dual ground planes (NGP=2) the precision of the results depends upon the number of ground plane images that are processed. See graduate theses for more details.

The computation time for dual conducting planes is based on the number of image reflection that the user desires. The number of images that require volume integration is 1+NGPI*2. The adaptive algorithm processes these reflected images very quickly.

6.9 NH

The number of sample points along the height of the inductor.

6.10 NW

The number of sample points across the width of the inductor.

6.11 R

The radius of left or right turns in mils. Defaults W*0.51 which gives very tight turns.

6.12 UP

An optional parameter in a “Left”, “Right” or “Straight” segment of an arbitrary inductor specification. To be used to route traces up/down to create

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helixes or to pass traces over one another. Defaults to 0. Do not use, has not been tested yet.

6.13 W

Width of the inductor trace in mils.

Appendix A.

Inductor specifications

```
; This uses the arbitrary inductor to specify experimental inductor #1
; The purpose of this is to test to ensure that the Arbitrary shape
; can give the same value as a built in shape. And it does
;
inductance_LF{
   NH 3              ; Number of sample points in height
   NW 5              ; Number of sample points across width
   L  30             ; Distance between cuts
   P  2.45           ; Precision factor (%)  --do not make greater than 2.7
   shape  arbitrary{
            H 1.35     ;Height = copper thickness
            W 50       ;Width = trace width
         straight{L=150}
         right{R=50}
         straight{L=900}
         left{R=50}
         straight{L=3200}
         left{R=50}
         straight{L=2500}
         left{R=50}
         straight{L=3200}
         left{R=50}
         straight{L=900}
         right{R=50}
         straight{L=150}
         }
}
```

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